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Evaluating the impact of CO_2 capture and storage on total efficiency: A lifecycle analysis

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ABSTRACT

This paper evaluates the impact of carbon capture and storage (CCS) on the total efficiency of natural gas and coal-fired power plants in various countries, with a focus on energy penalties. Unlike previous studies, which primarily examine efficiency losses within the conversion process, this work extends the analysis across the entire fuel lifecycle, providing a more comprehensive assessment. Total efficiency is calculated by accounting for energy consumption across all stages: fuel preparation (extraction, processing, transportation), power generation, and CCS operations. The findings reveal that CCS significantly reduces total efficiency, with thermodynamic efficiency losses exceeding 50 % in both natural gas and coal plants. Sensitivity analyses identify CO_2 capture and transportation as the most energy-intensive stages, critically influencing overall efficiency losses. While natural gas plants suffer greater penalties due to high fuel preparation demands, coal plants are more impacted by CCS-related energy consumption. The study underscores the need for optimized fuel logistics, advanced CO_2 capture technologies, and efficient transportation strategies to mitigate these penalties and enhance the feasibility of CCS as a decarbonization pathway.

1. Introduction

Since 2010, human-generated greenhouse gas emissions have increased by 12 %, largely linked to emissions in the energy sector (Shukla et al., 2022). One way to reduce carbon emissions is carbon capture and storage (CCS) technologies that capture between 80 and 99 % of CO_2 emitted in big facilities (Chao et al., 2021; Chen, 2022; Tatarczuk et al., 2023; Yadav and Mondal, 2022). CCS can play a critical role in decarbonizing fossil fuel plants. Though costly, CCS can become economically viable with incentives like carbon markets and tax credits, enabling significant CO_2 reductions (Fan et al., 2022). In addition, CCS policies can reduce energy consumption, lower carbon prices, and boost GDP of countries implementing it (Fan et al., 2024). Li et al. (2022) characterized the deployment of CCS technology as urgent and reported that delays could reduce the CO_2 mitigation potential by over 40 % (Li et al., 2022). These studies suggest CCS as an important solution for achieving carbon neutrality and global climate goals.

CCS includes CO_2 capture, transport, and storage. CO_2 capture involves the separation and capture of the CO_2 generated in a fossil fuel power plant and its compression to a high pressure to reduce its volume to make its transport and storage more efficient. The high energy demand of CO_2 compression (Tan et al., 2016), can be reduced when the concentration of impurities in the CO_2 stream is below 5 % (Posch and Haider, 2012). CO_2 capture represents approximately 75 % of the total CCS costs (Yadav and Mondal, 2022). Various technologies have been developed over the last decades to obtain high capture rates. Available choices include pre-combustion capture, post-combustion capture, and oxyfuel combustion.

Post-combustion capture is the most advanced technology to capture generated CO_2 in energy-conversion systems and can be realized with adsorption, membranes, or chemical absorption (Wang et al., 2011). Today, chemical absorption with monoethanolamine (MEA) is the only commercially available method (Osman et al., 2020) thanks to its high CO_2 capture rates of above 90 % (Global CCS Institute, 2022; Rochelle, 2009). Other solvents, like 2-amino-2-methyl-1-propanol, N-methyldiethanolamine or phase-change amines (e.g., DMX™) also offer promising performance (Karnwiboon et al., 2019; Ochedi et al., 2020; Vega et al., 2020). In addition, MEA remains the go-to solvent for CCS retrofitting thanks to its compatibility with the existing infrastructure and the wealth of operational data available (IEA, 2020). Nonetheless,

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MEA regeneration has high energy requirements (3.2–5.5 MJ/kg CO_2) while phase-change solvents can offer reduced energy consumptions (up to 40 % lower) via liquid-liquid separation during regeneration (Zhang et al., 2019). Furthermore, water-lean amines have demonstrated the potential to reduce heating demands (Heldebrant et al., 2017). As post-combustion capture can be easily retrofitted without major modifications to existing power plants, it is the prime choice for CCS implementation today (Doukelis et al., 2009; Kumar and Tiwari, 2022; Lungkadee et al., 2021). Recent studies have shown post-combustion capture efficiencies between 80 and 90 %, increasing with with improvements observed when using a heat-integrated stripper (Tatarczuk et al., 2023).

Once CO_2 is captured and compressed to a high pressure, it needs to be transported to a chosen storage location. Depending on factors like distance and scale, the appropriate transportation is chosen among pipeline, ship, truck, and rail (Yang et al., 2020). The most commonly used method is pipeline transportation, especially in cases that generate constant flow. The main constraints in pipeline transportation are temperature, pressure, and impurities, with minimum CO_2 concentration of 90 % (Peletiri et al., 2019). Gaseous or liquid CO_2 is considered for short-distance pipelines, while supercritical CO_2 is the preferred option for long-distance pipelines (Lu et al., 2020a). Using natural gas pipelines for this purpose poses important risks of leakage and contamination of populated areas. For this reason, energy companies build pipelines specifically for CO_2 transport (Vitali et al., 2021). If the construction of pipelines for CO_2 transportation is not economically viable, ship, rail or motor vehicles, can be considered. For ship-based transport, that has recently become more relevant due to the increase of offshore storage sites, the conditions of CO_2 must be as close to the triple point as possible (~0.7 MPa and 223 K) (Al Baroudi et al., 2021). Rail and truck transport can be reliable methods for small-scale transportation. While truck transportation has been shown to be an economically viable choice for up to 320 km and around 18t of liquid CO_2, rail cars are suitable to transport 80t of CO_2 for up to 1600 km, with reporting losses between 9 and 16 % (McKaskle et al., 2022).

The final stage of CCS is storage. CO_2 is typically stored in geological formations, such as deep saline formations, depleted oil or gas fields, and basalt formations. CO_2 can also be used for enhanced oil recovery (EOR). EOR can reduce the high cost of CCS implementation by injecting the captured CO_2 into oil reservoirs to enhance oil extraction (Guo et al., 2020; Zhang et al., 2021). To guarantee security, the long-term safety of storage with minimal CO_2 leakage must be ensured. Among the different possibilities, deep saline formations are regarded as the best option, given their widespread availability, accessibility, and storage potential (Mkemai and Bin, 2020). Although not as widely available, depleted gas and oil fields are also suitable sites for CO_2 storage. Impermeable caprocks there offer minimum leakage over the years since they have stopped hydrocarbons from reaching the surface before. Another geological storage option is basalt formations. These volcanic rock formations have the necessary characteristics (high porosity and permeability) to increase the reactivity with CO_2, converting it into mineral carbonites over time and making it an ideal medium for long-term storage of CO_2 (Gíslason et al., 2018; Kelemen et al., 2019; McGrail et al., 2014). A typical concern for CO_2 storage is the limited capacity. Nonetheless, geological analyses suggest that there is sufficient CO_2 storage capacity, with estimates between 8 and 55 thousand Gt of storage capacity, most of which is onshore (IEA, 2021). Storage also involves several risks and concerns, as it can induce seismicity and leakage to underground water (Paluszny et al., 2020). However, various projects show that, these risks are, in most cases, not a major reason to halt the progress in CO_2 storage (Kapetaki et al., 2017).

As CCS is regarded a promising technology to reduce carbon emissions, several countries have developed policies and initiatives to support CCS development and adoption. The United States have recently imposed a new regulation that requires coal and natural gas-fired power plants to implement CCS technologies if they want to continue in operation past 2040, while they also incorporated a tax credit to incentivize CCS adoption (IEA, 2023a). They estimate a reduction in CO_2 emissions of 1.5 billion tons annually (Tollefson, 2023). The European Union has also encouraged the adoption of this technology by means of its CCS Directive 2009/31/EC (European Parliament and Council, 2009) and various support campaigns, like the Innovation Fund or Horizon EU, that support CCS projects and development and innovation in the field (European Commission, 2022). Other countries and organizations have also shown their support to the development of CCS technology as well: Norway with the Longship Project (IEA, 2022), Canada with the Strategic Innovation Fund and the Low Carbon Economy Fund (Government of Canada, 2023a, 2023b), the United Kingdom with the CCS Infrastructure Fund (GOV.UK, 2022) and the International Energy Agency (IEA) with its support to the Clean Energy Ministerial initiative (IEA, 2023b).

Various attempts to introduce CCS technologies in fossil fuel power plants have been realized, with different levels of success. Two examples of successful CCS implementations are the SaskPower's Boundary Dam plant (Canada) and NRG's Petra Nova plant (USA), the only two commercial-scale coal-fired power plants using CCS in 2019. These plants incorporated post-combustion solvent-based CO_2 capture that captured about 90 % of the CO_2 generated (Mantripragada et al., 2019). Since then, CCS was implemented in other commercial-scale coal-fired power plants such as Shenhua Guohua Jinjie Energy in Shaanxi province or Taizhou coal-fired power plant in Jiangsu province, China (Patel, 2024). On the other hand, a pilot project for the implementation of CCS at the Schwarze Pumpe power station (Germany) with oxyfuel capture did not came into fruition due to the high costs and the resistance of the local community who did not want this technology in their neighborhood (Weber and Cabras, 2017).

Overall, CCS is a technology that can reduce CO_2 emissions from fossil fuels. However, CCS adoption is linked to an important increase in the specific capital costs and the price of electricity (Kheirinik et al., 2021), as well as a significant efficiency reduction that can reduce the overall benefits from CO_2 capture (Kennedy, 2020; Petrakopoulou, 2010; Petrakopoulou et al., 2012; Petrakopoulou and Tsatsaronis, 2014).

This paper studies the total efficiency of fossil fuel power plants with CCS, with a focus on chemical absorption for carbon capture. The relationship between the total reduction in emissions and total efficiency can evaluate CCS technologies in power generation consistently and reveal both the benefits and challenges of CCS implementation.

2. Methods

While other previous studies (Rubin et al., 2015; Wang et al., 2011) may have assessed efficiency losses due to CCS at the plant level, they have largely overlooked upstream energy penalties derived from fuel extraction, preparation and transport. Meanwhile, Koornneef et al. (2008) applied a lifecycle assessment (LCA) on CCS, although focusing narrowly on capture stages, omitting key elements such as the variability in the electricity grid mix (Pehnt, 2006). The calculation of total efficiency was first introduced by Petrakopoulou and Corcuera (2022, 2023)(Petrakopoulou and Corcuera, 2022; Petrakopoulou and García-Tenorio, 2023). This approach fills the gaps by combining LCA principles with operational efficiency metrics, following recommendations by Bui et al. (2018). For example, Equation (4) below integrates country-specific electricity profiles (Turconi et al., 2013), allowing for a more comprehensive evaluation of CCS impacts an aspect not fully addressed in earlier studies. The energy costs of the production (*prod*), processing (*proc*) and transportation (*trans*) of the fuel used in all energy-conversion steps of a process, are used to calculate the total energy requirement of the overall process and its total efficiency. The different subprocesses are split into direct (*d,* fuel-driven) and indirect (*in,* electricity-driven):

$$C_{d,i} = \frac{F_c \cdot LHV_f}{m_f} \text{ (units : MJ / kg)} \tag{1}$$

$$C_{in,j} = \frac{Elec_c \cdot PR}{m_f} \cdot \left[A \cdot \frac{1}{\eta_{pp}} + \frac{(1-A)}{\eta_{pp,a}} \right] \text{ (units : MJ / kg)} \tag{2}$$

where, $C_{d,i}$ is the fossil fuel use in a direct process, F_c is the mass of the needed fuel to process and make the fossil fuel ready for use (in kg), LHV_f is the lower heating value (LHV) of the fuel used (in MJ/kg), $C_{in,j}$ is the fossil fuel use in an indirect process, A is a constant that receives the value of 1 if part of the consumed electricity is generated using fossil fuels and 0 if the electricity origin is unknown, $Elec_c$ is the consumed electricity (in MJ), $E_{mix,p}$ is the percentage of electricity obtained from fossil fuels in country p (without units) (Ritchie et al., 2020), PR is the percentage of electricity from fossil fuels (without units), η_{pp} is the conventional efficiency of the fossil-fuel plant generating the electricity required to make the fuel available for use (without units), $\eta_{pp,a}$ is the average conventional efficiency of fossil-fuel power plants in the considered country p (without units), and m_f is the mass of fuel produced (in kg).

The total energy cost of the preparatory stages of fossil fuels can be calculated as the sum of the costs at each stage of fossil fuel preparation:

$$C_t = C_{prod} + C_{proc} + C_{trans} \text{ (units : MJ / kg)} \tag{3}$$

Since all subprocesses can be split into direct and indirect as presented in Equations (1) and (2), the total energy requirement of each of the different stages can be defined as the sum of the included direct and indirect subprocesses. Combining Equations (1)–(3) we obtain the general equation for the calculation of the total energy requirement of a fuel's lifecycle:

$$Cons_{trans,pipe} = \frac{1}{CO_{2trans} \cdot \rho_{CO_2}} \cdot \frac{n_C \cdot P_C}{\dot{V}} \cdot \frac{D}{R_{station}} \left(A \cdot \frac{1}{\eta_{pp}} + (1-A) \cdot E_{mix,p} \cdot \frac{1}{\eta_{pp,a}} \right) \text{ (units : MJ / kg } CO_2) \tag{8}$$

$$C_t = \sum C_d + \sum C_{in} \Rightarrow$$

$$C_t = \frac{1}{m_f} \left\{ \sum_i (F_c \cdot LHV_{f,c}) + \sum_j \left\{ Elec_c \cdot \left[A \cdot \frac{1}{\eta_{pp}} + (1-A) \cdot E_{mix,p} \cdot \frac{1}{\eta_{pp,a}} \right] \right\} \right\} \text{ (units : MJ/kg)} \tag{4}$$

This work further introduces the energy required for CCS in the calculation of total efficiency. When looking specifically at CCS, four stages are included: capture, processing, transport, and storage of the CO_2. All direct and indirect processes involved in these four steps are considered. Here, m_f of Eq. (4) is replaced with m_{CO2}:

$$C_{CO_2} = \sum C_d + \sum C_{in} \Rightarrow$$

$$C_{CO_2} = \frac{1}{m_{CO_2}} \left\{ \sum_i (F_c \cdot LHV_{f,c}) + \sum_j \left\{ Elec_c \cdot \left[A \cdot \frac{1}{\eta_{pp}} + (1-A) \cdot E_{mix,p} \cdot \frac{1}{\eta_{pp,a}} \right] \right\} \right\} \text{(units : MJ / kg)} \tag{5}$$

Equation (5) is subject to several assumptions. The energy cost of CO_2 capture, for example, depends on the capture method used. This study focuses on post-combustion capture with chemical absorption using monoethanolamine. A percentage range of CO_2 capture from 85 to nearly 100 % and a wide range of energy requirement for the regeneration of the solvent are evaluated, based on recent literature. The processing step of the CO_2 captured in the plant is considered to be its compression.

While the calculation of the energy requirements of the capture, processing and storing of the CO_2 are straightforward, the CO_2 transport depends on several factors, like distance, the number of compressor stations at pipelines or a truck's engine fuel consumption. In the following, Equation (5) is adjusted to account for different transport possibilities:

The first case is truck transport, where the consumption can be expressed as:

$$C_{trans,truck} = \frac{1}{m_{CO_2,t}} \cdot C_{km} \cdot \rho_f \cdot LHV_f \cdot D \text{ (units : MJ / kg } CO_2) \tag{6}$$

where, $m_{CO_2,t}$ is the mass of transported CO_2 (in kg), C_{km} is the fuel consumption of the truck (in m^3 per kilometer), ρ_f is the density (in kg/m^3) of the fuel used to power the truck, and D is the distance the CO_2 is transported for (in kilometers).

In the case of tanker transport, the energy cost is calculated as:

$$Cons_{trans,tanker} = \frac{1}{m_{CO_2,t}} \cdot C_{km} \cdot \rho_f \cdot LHV_f \cdot D \text{ (units : MJ / kg } CO_2) \tag{7}$$

For other cases, such as pipeline transportation, the energy requirement of the stage can be estimated with two different equations (Petrakopoulou and Corcuera, 2022).

a. Considering the number of compressor stations along the pipeline:

where, CO_{2trans} is the mass of transported CO_2, ρ_{CO2} is the density of CO_2, n_C is the number of compressor stations along the pipeline (without units), P_C is the power required by the compressors (in MW), $R_{station}$ is the distance between the compression stations (in kilometers), and $\dot{V}$ is the volumetric flow of the transported CO_2 (in m^3/s).

b. When the volumetric flow in the pipeline is unknown:

$$Cons_{trans,pipe_b} = \frac{D}{R_{station}} \cdot Elec_c \cdot \left(A \cdot \frac{1}{\eta_{pp}} + (1-A) \cdot E_{mix,p} \cdot \frac{1}{\eta_{pp,a}} \right) \text{(units:MJ/kg}CO_2) \tag{9}$$

The energy requirements of each stage of the fossil fuel preparation and the CO_2 process are then used to calculate the total efficiency of the plant. The derivation of total efficiency starts from the conventional efficiency (η_{conv}):

$$\eta_{conv} = \frac{\dot{W}_{NET}}{\dot{Q}_f} = \frac{\dot{W}_{NET}}{\dot{m}_f \cdot LHV_f} \text{ (without units)} \tag{10}$$

where, $\dot{W}_{NET}$ & $\dot{Q}_f$ are the net power produced in the plant and the input heat from the fuel, respectively, in MW.

Introducing the total energy costs of the fossil fuel's lifecycle and the CCS process in Equation (10), results in the following expression of total efficiency:

$$\eta_{total_{PP}} = \frac{\dot{W}_{NET}}{\dot{Q}_f + F_{LC} + E_{CCS}} \text{(without units)} \quad (11)$$

where, F_{LC} is the total energy requirement per kg of fuel over its lifecycle (in MJ/kg fuel), and E_{CCS} is the total energy requirement per kg of CO_2 captured (in MJ/kg CO_2).

Equation (11) can be further refined using the following expressions:

$$- F_{LC} = \dot{m}_f C_t \text{ (units : MJ/kg fuel)} \quad (12)$$

$$- E_{CCS} = \dot{m}_{CO_2} C_{CO_2} \text{(units : MJ/kg CO}_2\text{), and} \quad (13)$$

$$- r_{CO_2} = \frac{\dot{m}_{CO_2}}{\dot{m}_f} \text{ (without units)} \quad (14)$$

The final, detailed form of total efficiency is shown in Equation (15):

$$\eta_{total_{PP}} = \frac{\dot{W}_{NET}}{\dot{m}_f \cdot LHV_f + \dot{m}_f C_t + \dot{m}_{CO_2} C_{CO_2}} = \frac{\dot{W}_{NET}}{\dot{m}_f \cdot LHV_f + \dot{m}_f C_t + \dot{m}_f r_{CO_2} C_{CO_2}} = \frac{\dot{W}_{NET}}{\dot{m}_f \left(LHV_f + C_t + r_{CO_2} C_{CO2} \right)} \text{ (without units)} \quad (15)$$

where, $\dot{m}_f$ is the mass flow of fuel (in kg/s) in the power generation cycle, $\dot{m}_{CO_2}$ is the mass flow of CO_2 (in kg/s) captured and r_{CO_2} is the rate of CO_2 captured.

In addition to the calculation of total efficiency, the final quantity of CO_2 captured (or total emissions of the plant) is also evaluated. A sensitivity analysis of the captured CO_2 is realized, with capture in the range between 85 and 100 %. All calculations consider the share of total CO_2 captured, and the impact the complete CCS process has on the operation of the plants.

3. Case studies

The steps before and after power generation, i.e., the process to make the power plant fuel ready for use and then capture, transport, and store the CO_2, require significant amounts of energy input. The location of the power plant also greatly influences this energy requirement, especially in countries that need to import the required fuel and those whose power grid heavily relies on fossil fuels.

To study the impact of CCS on efficiency, two fossil fuels are studied: a natural gas and coal-fired power plant. The study is replicated in two countries: the United Kingdom (UK) and Australia. Four main case studies (CS) are defined based on the country and the fuel (coal and natural gas). Further subcases are defined based on the used fuel, the transport means and the storage site.

The power plants analyzed are hypothetical and are each equipped with an identical chemical-absorption unit using monoethanolamine, selected for its widespread commercial use and high CO_2 capture efficiency. All necessary data are derived from published studies appropriately cited.

To distinguish among all cases and subcases, the nomenclature CSP-F.T.S is used.

- P is the code identifying the country where the plant is located: *U* for the UK, and *A* for Australia.
- F is the code identifying the fossil fuel: *N* for natural gas, and *C* for coal.
- T is the code identifying the fuel transport:

o *pip* for pipeline and freight train transport, and
o tr for train transport.

- S is the code identifying the CO_2 storage:

o *UW* for underwater storage, and
o *UG* for underground storage.

For example, the subcase of coal use in Australia, freight train transport, and CO_2 underground storage is identified as CSA-C.pip.UG.

The natural-gas plant is a combined-cycle power plant with four 900 MW (NG) units and a conventional efficiency of 57 % (Shell, 2016). The coal-fired power plant has four units of 600 MW and a conventional efficiency of 37 % (Department of Trade and Industry, 2000). Both sites are considered to be relatively close to the extraction sites of the used fossil fuels.

Natural gas will be transported to the plant via pipelines from a field 290 km away from the plant, while coal will be extracted and transferred to the plant from a mine located 290 km away from the plant, via train. To perform a more comprehensive assessment on each subprocess's impact on total efficiency, a sensibility analysis has been performed.

The CO_2 captured is compressed and transported to a storage site. Two alternatives are considered here. In the first case, the CO_2 is transported via pipelines to a depleted gas reservoir 440 km away from the power plants. In the second case, the CO_2 is injected underground, implying transport of 80 km for both plants.

The study's reference cases are established using the average values for coal and natural gas preparation from Tables 1 and 2, along with the mean energy requirements for 95 % CO_2 capture from Table 3. These cases are then refined into subcases, integrating different alternatives for CO_2 transport and storage.

The thermal energy for CO_2 capture is assumed to be covered internally by each power plant. Other assumptions made to calculate the energy requirement for fuel preparation are the following.

1. Extraction and processing

a. LHV of coal: 27.54 MJ/kg.
b. LHV of diesel: 42.60 MJ/kg.
c. LHV of gasoline: 43.4 MJ/kg.
d. LHV of NG: 47.10 MJ/kg.

2. Transportation

a. In CSP-N.pip.S, the pipeline distance is 290 km and includes 3 compressor stations. This assumption is based on the work of

Table 1
Energy requirement for the preparation of natural gas.

Stage	Value	Reference
Extraction	12.8773 MJ/m^3 NG 20–30 m^3 diesel/d 57 million m^3/year	Riva et al. (2006) IPIECA (2013)
	Electrical installation: 500 MW	(Myhre and Chr., 2001)
	Electrical installation: 25 MW Electrical installation: 5.5 MW	Nguyen et al. (2016)
Processing at gas field	96.52 MMBTU/h per 100 MMscfd 1613 MMBTU/h per 600 MMscfd	Khoshnevisan et al. (2021)
	12.64 MW$_e$ per 14 MSm^3/d 2.2 MW$_e$ per 7.6 MSm^3/d	Kidnay et al. (2011)
Gas field – CSP-U pipeline transport	Volumetric Flow: 12.054 dam^3/d Diameter: 20 inches 0.75 MW/compressor station	(Liu et al., 2014; Shell U. K., 2020)
	Compressor requirement: 3.818 MJ/kg	Elgqvist et al. (2021)

Table 2
Energy requirement for the preparation of coal.

Stage	Value	Reference
Extraction	365.81 MJ_t/t	Dones et al. (2007)
	50.04 MJ_e/t	
	43.7576 kWh_e/t	Burchart-Korol et al. (2016)
	69.8 MJ_t/t	
	21.3 kWh/t	Mu and Wang (2015)
	1.3E-04 t_{diesel}/t	
	2.54E-05 $t_{gasoline}/t$	
	3.88E-03 t_{coal}/t	
Processing at mine facilities	174.6 MJ_e/t	Dones et al. (2007)
	9.2348 kWh_e/t	Burchart-Korol et al. (2016)
	32.4 MJ_e/t	Mu and Wang (2015)
Internal belt conveyor transport	Transport capacity: 1000 t/h Electrical power: 57 kW	Ji et al. (2020)
Freight train	3.24–4.32 MJ/t·km	Garcia-Alvarez et al. (2013)
Truck	0.35 l_{diesel}/km	España Ministerio de Transportes (2023)

Table 3
Energy requirement of the CCS process.

Stage	Value	Reference
CO_2 capture	3.2–5.5 $MJ_t/kg\text{-}CO_2$	Luis (2016)
	3.6–3.8 $MJ_t/kg\text{-}CO_2$	Biermann et al. (2022)
	120 $kg\text{-}CO_2/h$	
	0.89 $MJ_t/kg\text{-}CO_2$ @ 100 % capture	Lee et al. (2023a)
	3.9 $MJ_t/kg\text{-}CO_2$	
CO_2 compression	0.288–0.432 $MJ_e/kg\text{-}CO_2$	Jackson and Brodal (2019)
	0.234 $MJ_e/kg\text{-}CO_2$	Bisinella et al. (2021)
CO_2 transport	15–17 MW_e	Lu et al. (2020b)
	9.8 MPa	
	12.054 dam^3/d	
CO_2 storage	Injection rate: 1.5 $kg\text{-}CO_2/s$	Vilarrasa et al. (2013)
	409.6 kW_e (gas phase)	
	368.2 kW_e (near-critical point)	
	361.9 kW_e (supercritical phase)	
	154.7 kW_e (liquid-phase: high T and p)	
	83.6 kW_e (liquid-phase: low T and p)	
	Injection rate: 31.7 $kg\text{-}CO_2/s$	Wu and Li (2020)
	30–35 MW_e	

Witkowski et al. (2018) that estimated that the maximum safe transport distance for an 84-bar pipeline is 100 km (Witkowski et al., 2018)

b. In CSP-C.tr.S, the railway distance is 290 km.

The assumptions to calculate the energy requirement of CCS are the following.

1. CO_2 transportation

a. In CSP-F.T.UG, the pipeline distance is 80 km and includes 1 compressor station.
b. In CSP-F.T.UW, the pipeline distance is 440 km and includes 5 compressor stations.

2. Electricity generation:

a. When electricity input is required, the electricity mix of the country is considered (Ritchie and Rosado, 2020):

i. UK:

1. Fossil fuels account for 39.92 % of the power grid,
2. Natural gas makes up 96.13 % to that share, and
3. Coal contributes 1.38 % to the fossil fuel portion.

ii. Australia:

1. Fossil fuels account for 63.93 % of the power grid.
2. Natural gas makes up 25.12 % to that share, and
3. Coal makes up the remaining 74.88 % of the fossil fuel portion.

b. The efficiency of the natural gas power is assumed to be 49 % (Statista Research Department, 2024a).
c. The efficiency of the coal power plants is assumed to be 35.8 % (Statista Research Department, 2024b).
d. The efficiency of the boiler is 98 %.
e. The mass flow rate of NG in the natural gas plant is 36.05 kg/s. This figure was calculated based on the efficiency of the power plant, its output and the lower heating value of natural gas.
f. The mass flow rate of coal in the coal plant is 55.92 kg/s. This figure was calculated based on the efficiency of the power plant, its output and the lower heating value of coal.

These assumptions, together with the data presented in Tables 1–3, that present the energy requirements of each subprocess according to recent publications, have been used to evaluate the different scenarios (see Fig. 1).

4. Results and discussion

The total energy requirement in the different cases is analyzed in terms of MJ of total fuel input per MW of net electricity generated in the plants (MJ/MW_{net}). Fig. 2 illustrates the energy requirements of the four subprocesses considered: fuel extraction, processing, transportation, and CCS implementation, for both coal and natural gas plants.

The primary focus is on CCS integration. The data for CO_2 capture, compression, transportation, and storage at the plant in the reference cases are based on mean values of the ranges presented in Table 3. It is assumed that the reference plants capture 95 % of the generated CO_2.

Figs. 2 and 3 presents the contribution of CCS in each CS. Two key differences can be observed from these figures. First, the substantial total energy requirement difference between the two fuels studied (1.25–1.29 vs. 0.45–0.46 MJ/MW_{net} in the UK, and 1.48–1.54 vs. 0.47–0.48 MJ/MW_{net} in Australia), and, second, the difference in the energy requirement between the two countries (0.23–0.25 MJ/MW_{net} difference for natural gas, and 0.2 MJ/MW_{net} for coal). The differences between the fuel sources can be primarily traced back to the elevated values of the preparation stages (extraction, processing, and transport) of natural gas, that is not the case for coal. On the other hand, the differences between the two countries are stem from variations in their electricity mix, with Australia being 60 % more dependent on fossil fuels than the UK.

The influence of fuel preparation stages on the total energy requirement differs significantly between the CSs, especially when comparing natural gas and coal. While the preparation stages are linked to 82–85 % of the total energy requirement in CSU-N, they only contribute 10 % of the total energy requirement in CSU-C. A similar trend is seen in the Australian CSs, where the preparation stages account for 81–84 % of the total energy requirement in CSA-N, but only 7 % in CSA-C. Consequently, while the effect of CCS on the total energy requirement in CSP-N is relatively low (ranking third among the four stages considered), its effect in CSP-C is very significant, and exceeds that of any other stage. With 95 % CO_2 capture, the CCS energy requirement is 0.21–0.25 MJ/MW_{net} in CSU-N, and 0.45 MJ/MW_{net} in CSU-C; and 0.23–0.28 MJ/MW_{net} in CSA-N, and 0.45–0.46 MJ/MW_{net} in CSA-C. While these relative values highlight a substiantial difference in the CCS impact between the two fuels, the absolute energy requirement values reveal that CCS for coal (CSU-C and CSA-C) demands twice as

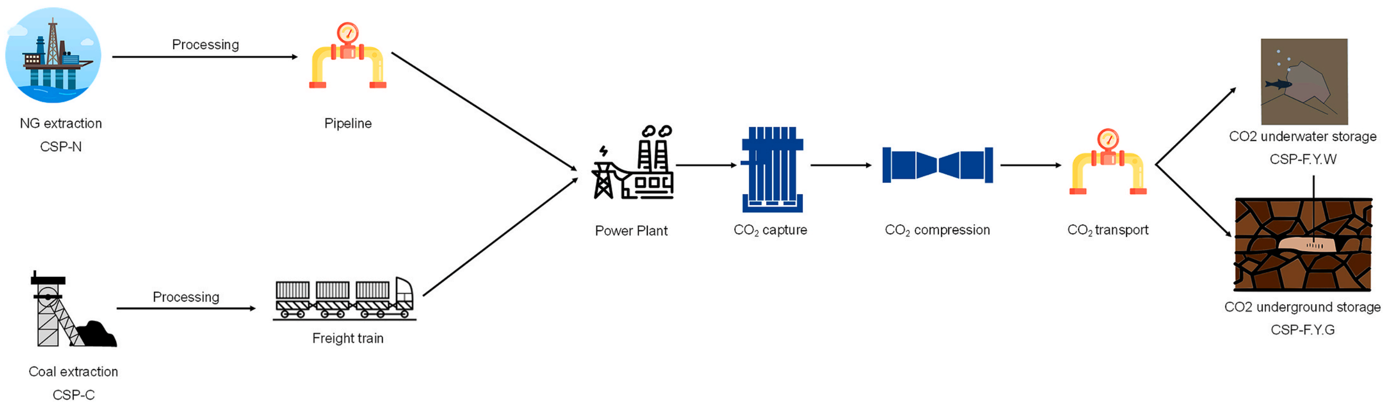

Fig. 1. Schematic of the fuel preparation steps and CCS in the case studies.

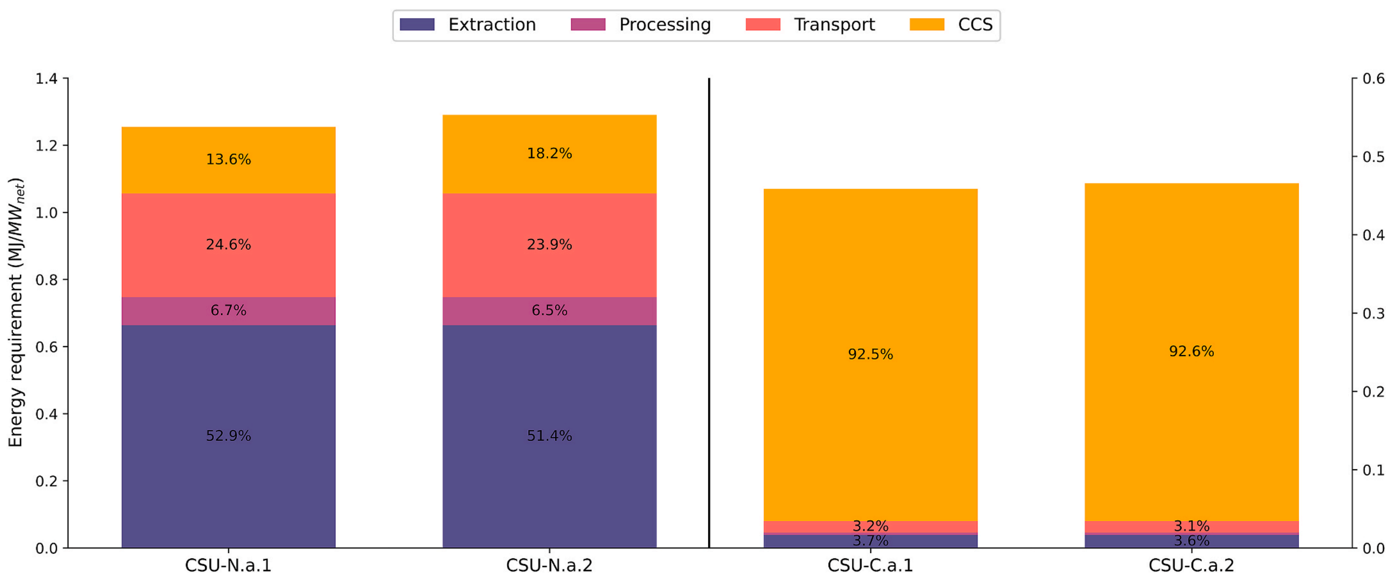

Fig. 2. Average energy requirement and contribution share to the total energy requirement (shown in percentages) of the fuel preparation and CCS stages in the UK. The left y-axis represents energy requirements (MJ/MWnet) for the first 2 bars, while the right y-axis corresponds to the last two.
Values below 0.6 % (processing) are omitted for clarity in visualization.

much energy as for natural gas (CSU-N and CSA-N).

Lastly, although not immediately apparent in Figs. 2 and 3, a key distinction between the two fuels studied (CSP-N and CSP-C) lies in their mass flows within the power generation cycle. Natural gas produces over 230 % power per unit of fuel compared to coal. This disparity becomes more evident when comparing the CCS energy requirements (in MJ/MW$_{net}$) for all case studies, as there are no additional differences between them. This highlights the difference in the energy content between natural gas and coal (47.10 vs. 27.54 MJ/kg LHV) – coal requires significantly more mass than natural gas to produce the same energy output, as natural gas provides 71 % more energy per kilogram.

Figs. 4 and 5 shows the contribution of CCS to the final energy requirement, highlighting its impact of the subprocesses defined. These figures present the difference in energy output per unit mass of fuel. Additionally, the country-specific differences in power plant location are reflected in the compression process, where the electricity mix of each country plays a significant role. Furthermore, CO_2 capture is clearly the most energy-intensive subprocess, resulting in 0.15 MJ/MW$_{net}$ in CSP-N and 0.35 MJ/MW$_{net}$ in CSP-C. This accounts for more than 60 % of the total CCS energy requirement in both CSs.

To evaluate the impact of CO_2 capture, the CO_2 capture rate of the plants is varied between 85 and 100 % (Table 4 and Figs. 6 and 7). Perfect combustion, i.e., no CO production, is assumed in all cases. Potential improvements in processes or technologies, such as the energy requirement for fuel extraction, have not been evaluated and are considered constant.

Figs. 6 and 7 present the calculated CO_2 emissions for both CSs. These values result from calculating the additional fuel required to support the CCS system based on the extra energy needed to maintain constant power output. For instance, in the reference CSs with 95 % CO_2 capture, CSP-N consumes 45.85 kg/s of natural gas in the UK and 46.01 kg/s in Australia, generating 126.08 kg CO_2/s and 126.53 kg CO_2/s, respectively. On the other hand, CSP-C burns 79.32 kg/s of in the UK and 80.24 kg/s in Australia, emitting 290.77 and 294.16 kg CO_2/s, respectively. With 100 % CO_2 capture, the fuel requirement to maintain constant power output increases to 46.36 kg/s of natural gas in the UK and 46.53 kg/s in Australia, and 80.55 kg/s of coal in the UK and 81.52 kg/s in Australia.

Assuming a capacity factor (C_f) of 90 % for the two power plants, substantial annual emission savings are achievable. In CSP-N, emission savings could reach 3.4 Mt CO_2/year, while in CSP-C more than double those savings can be reached, with up to 7.9 Mt CO_2/year avoided.

Figs. 8 and 9 shows the median value of total efficiency in the two power plants with CO_2 capture rates between 85 and 100 % and the

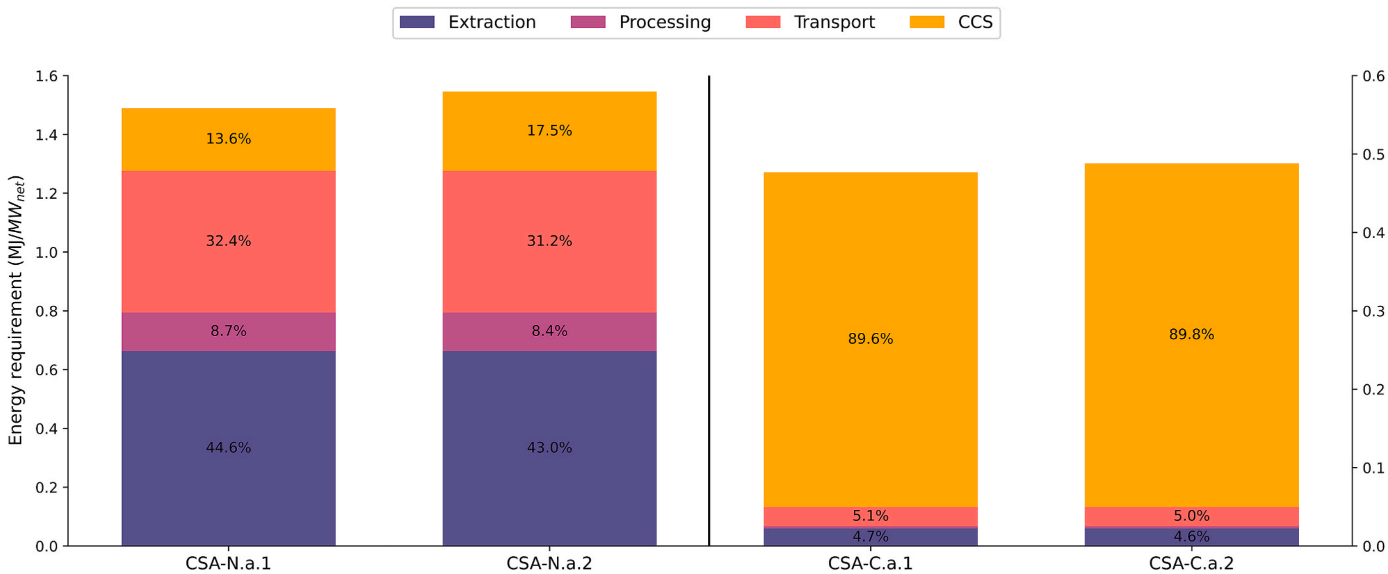

Fig. 3. Average energy requirement and contribution share to the total energy requirement (shown in percentages) of the fuel preparation and CCS stages in Australia. The left y-axis represents energy requirements (MJ/MWnet) for the first 2 bars, while the right y-axis corresponds to the last two.
Values below 0.6 % (processing) are omitted for clarity in visualization.

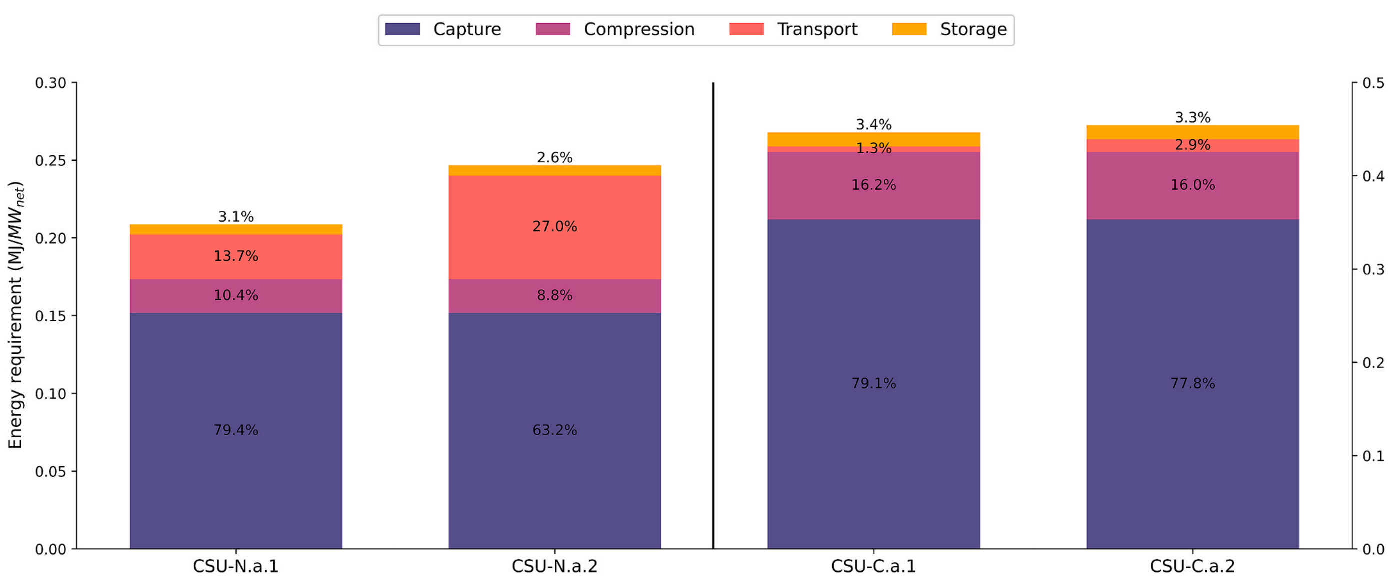

Fig. 4. Energy requirement and contribution shares (shown in percentages) of CCS stages of the case studies in the UK. The left y-axis represents energy requirements (MJ/MWnet) for the first 2 bars, while the right y-axis corresponds to the last two.

relative efficiency decrease compared to the same plant without CCS. The error bars illustrate the variability in the calculations when the complete range of values reported in literature for the different stages is accounted for (see Tables 1–3). The error bars span from the minimum to the maximum values but exclude outliers (data points more than 1.5 times the interquartile range above the third quartile or below the first quartile).

Total efficiency is maximum at the lowest CO_2 capture rate. For CSU-F, with an 85 % capture rate, natural gas has a total efficiency of 31.62 %, while coal reaches 22.82 %. This corresponds to efficiency drops of 44.51 % in CSU-N and 59.84 % in CSU-C. With 100 % CO_2 capture, total efficiency decreases to 30.79 % (45.99 % efficiency drop) in CSU-N and 21.42 % (62.31 % efficiency drop) in CSU-C. For CSA-F, total efficiencies of 29.84 % and 22.39 % are found for natural gas and coal, respectively, at an 85 % capture rate, leading to efficiency drops of 47.66 % in CSA-N and 60.60 % in CSA-C. At 100 % CO_2 capture, total efficiency falls to 29.06 % in CSA-N (a 49.01 % efficiency drop) and 20.98 % (a 63.08 % efficiency drop) in CSA-C. These values show the differences between CSP-N and CSP-C in terms of CCS impact, with higher CO_2 capture rates imposing stronger efficiency penalties in CSP-C. Significant penalties are also observed in CSP-N, primarily due to the assumed maximum and minimum values of natural gas extraction (Riva et al., 2006).

Figs. 10 and 11 show the total efficiency and efficiency drop in each CS when excluding the preparatory stages of fuel. This approach allows for a clearer assessment of the impact of CCS, as it deletes the influence of other factors.

The impact of CCS becomes evident when comparing Fig. 8/9 and 10/11. In CSP-N, CCS contributes an average of 13.6–18.2 % to the total energy requirement, whereas in CSP-C the impact is significantly higher, ranging from 89.6 to 92.6 %. When fuel preparation is excluded, the median maximum total efficiency in CSU-N reaches 42.70 %, corresponding to a 24.95 % efficiency drop, which represents a 35 %

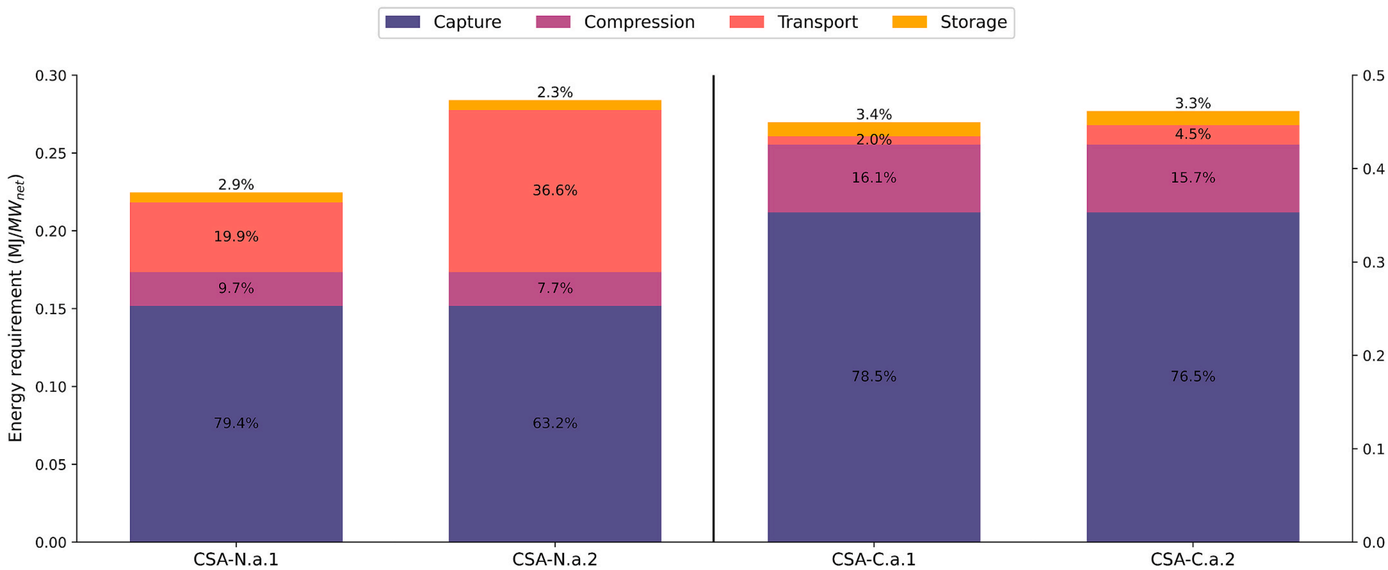

Fig. 5. Energy requirement and contribution shares (shown in percentages) of CCS stages of the four case studies in the UK. The left y-axis represents energy requirements (MJ/MWnet) for the first 2 bars, while the right y-axis corresponds to the last two.

Table 4
Captured CO_2 and CO_2 emissions of the case studies for different CO_2 capture rates.

Capture %	Natural gas (kg CO_2/kg NG)		Coal (kg CO_2/kg NG)	
	Captured CO_2	CO_2 Emissions	Captured CO_2	CO_2 Emissions
0 %	0	2.75	0	3.39
85 %	2.34	0.41	2.88	0.51
90 %	2.48	0.28	3.05	0.34
95 %	2.61	0.14	3.22	0.17
100 %	2.75	0.00	3.39	0.00

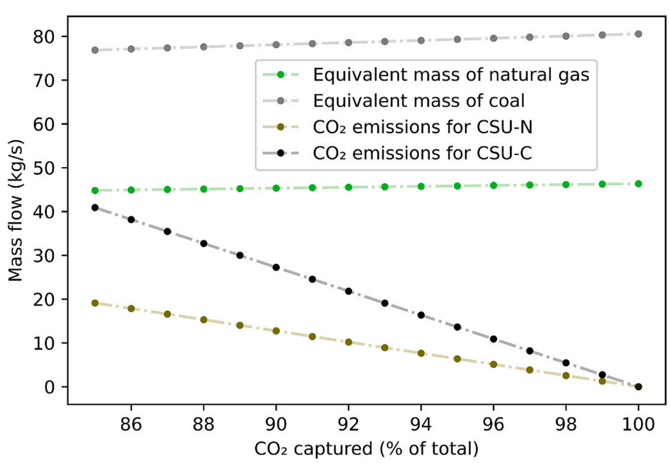

Fig. 6. Equivalent mass flow of fuel and CO_2 emissions for different CO_2 capture ratios in the UK.

improvement compared to the values of Figs. 8 and 9. In CSA-N the median maximum total efficiency is 42.55 % with a 25.20 % efficiency drop, showing a 42.6 % improvement. Conversely, in CSU-C the median maximum total efficiency is 23.06 %, with a 59.44 % efficiency drop, showing little variation. In CSA-C the median maximum total efficiency is 22.70 % with a 60.08 % efficiency drop, reflecting only a 1.38 % improvement. At 100 % CO_2 capture, these values shift to 41.28 % for natural gas and 21.62 % for coal in CSU-F, with efficiency drops of 27.42 and 61.96 %, respectively. In CSA-F, total efficiency decreases to 41.12

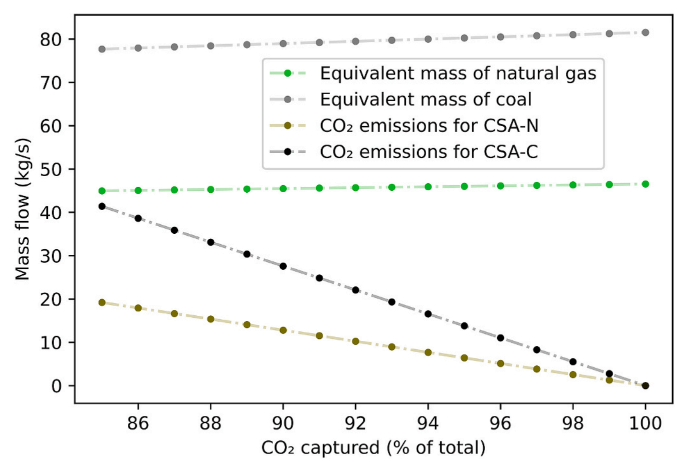

Fig. 7. Equivalent mass flow of fuel and CO_2 emissions for different CO_2 capture ratios in Australia.

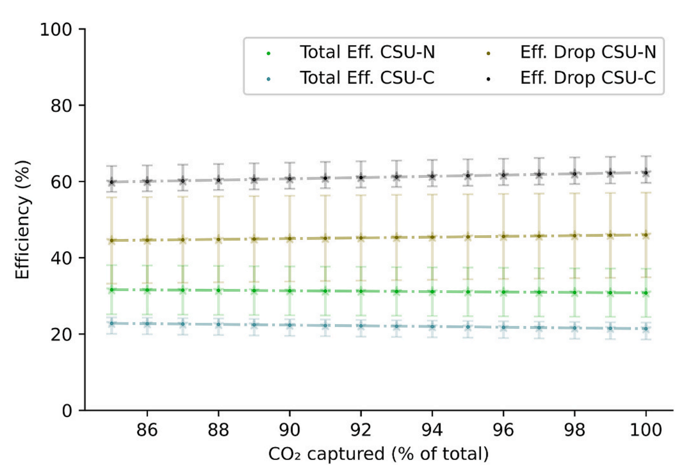

Fig. 8. Total efficiency and efficiency drop relative to the plant without CO_2 capture in the UK.

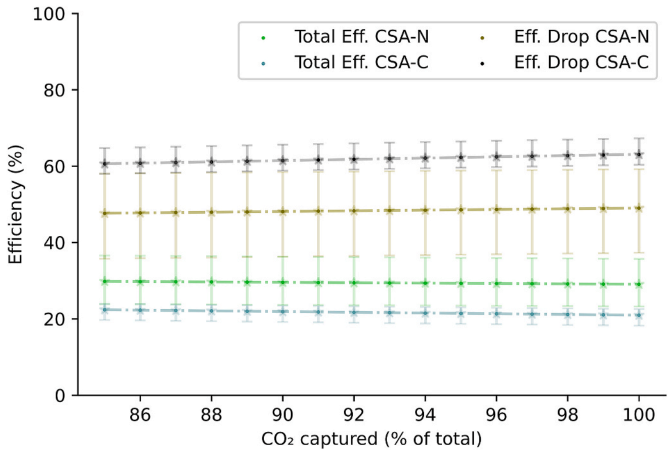

Fig. 9. Total efficiency and efficiency drop relative to the plant without CO_2 capture in Australia.

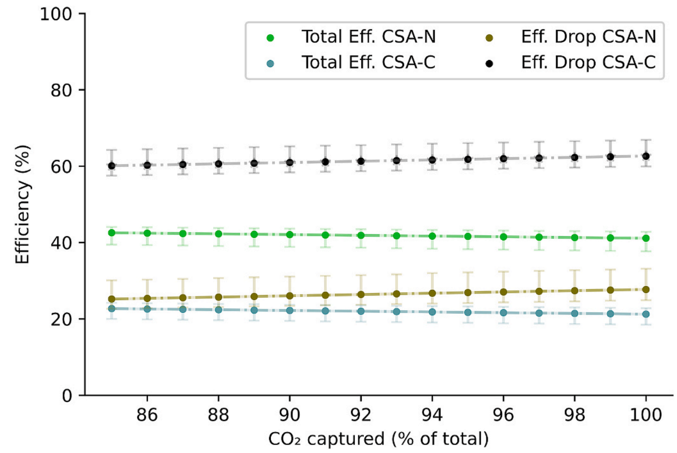

Fig. 11. Total efficiency and efficiency drop relative to the plant without CO_2 capture and without accounting for the fuel preparation stages, in Australia.

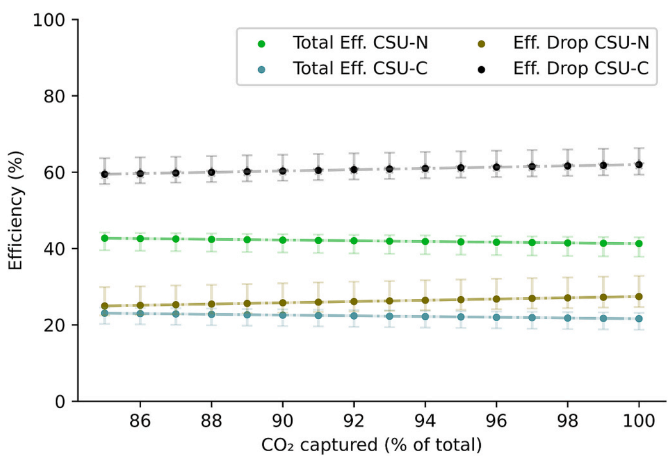

Fig. 10. Total efficiency and efficiency drop relative to the plant without CO_2 capture and without accounting for the fuel preparation stages, in the UK.

% for natural gas and 21.25 % for coal, with drops of 27.71 and 62.62 %, representing a negative change of 0.33 % in CSP-N and 0.6 % in CSP-C. This reveals the strong influence of fuel preparation mainly on CSP-N, where the efficiency-drop almost doubles when fuel preparation stages are included.

Integrating CCS inevitably reduces the efficiency of the plants, as capture and compression require additional power implies a higher fuel consumption. However, this efficiency drop represents just one aspect of the equation. On the other hand, significant reductions in CO_2 emissions are achieved when CO_2 capture approaches 100 %, at 90 % C_f: 3.6 Mt/year in the natural gas power plant (CSP-N) and 8.43 Mt/year in the coal power plant (CSP-C). Looking at the emissions per net power output, CSP-N avoids 4 kt CO_2/MW_{net} per year, while CSP-C avoids 14.05 kt CO_2/MW_{net} per year.

The significant efficiency losses identified in this study highlight the need for operational improvements and supportive policy measures alike. Technologically, heat-integrated strippers can help reduce the energy required for solvent regeneration by 15–20 % (Tatarczuk et al., 2023), while hybrid solvents which combine MEA with phase-change amines (Lee et al., 2023b) may help lower energy demands. Economically, carbon pricing policies (e.g., \$50/tCO_2) could alleviate the levelized cost for power plants with CCS (offsetting costs by 8–12 %), encouraging retrofits without compromising grid reliability (Fan et al., 2022).

The impact of CCS on total efficiency is evident in both power plants analyzed. When compared to previous studies on total efficiency (Petrakopoulou and García-Tenorio Corcuera, 2022), this influence is even more pronounced. These earlier studies reported efficiency drops between 14 and 21.5 % for natural gas power plants, whereas the present study finds a maximum drop of 27.71 %. Similarly, for coal power plants previous studies observed efficiency losses between 22.66 and 25.27 %, while the present study reports a much higher maximum drop of 62.62 %.

To investigate this further, a sensitivity analysis of the transportation distance of the used fuel is conducted. Other factors affecting total efficiency (and consequently total energy requirement) are kept constant. The variation of the energy requirement for fuel extraction is based on literature data and the mass flow rate of the fuel, along with the resulting CO_2 emissions, remains constant.

4.1. Sensitivity analysis

In this sensitivity analysis, all parameters used in the calculation of total efficiency have been modified by a factor of ±15 %. The results are presented in Table 5 through 10, with each table corresponding to one of the countries where the power plants are analyzed. These table show the total efficiencies and efficiency drops for each subcase. Additionally, the deviation (in percentage) from the baseline is included in parenthesis for a clearer comparison.

Table 5 through 7 show the results for CSU-F, where the largest deviations from the reference case (0 % change) are observed in natural gas transportation, driven by changes in distance, and CO_2 capture. These parameters result in total efficiency variations of 3 % and 2.1–4.3 % (CSU-N – CSU-C), respectively. Similarly, Table 8 through 10, which show the results for CSA-F, reveal the same key trends. Here, natural gas transportation and CO_2 capture continue to be the most influential parameters, with total efficiency deviations of 3.6 % and 1.99–4.16 %, respectively, when subjected to a ± 15 % variation. For CSP-C, the largest contribution from coal preparation stages is during the transportation stage, accounting for 0.05 % in CSU-C and 0.07 % in CSA-C, though these values remain negligible compared to the overall impact of CCS. Additionally, energy contribution across coal preparation stages in CSP-C are distributed more evenly among parameters than in CSP-N, where certain stages have a more pronounced impact.

A key observation is that transportation distance plays a major role in the final energy consumption of both coal and natural gas plants, particularly for natural gas plants. When transportation distance doubles, total efficiency drops 15.13 % in CSU-N and 16.62 % in CSA-N, highlighting the significant influence of fuel transport on overall efficiency, highlighting the significant influence of fuel transport on overall efficiency.

Table 5
Sensitivity analysis of natural gas preparation stages in CSU-N.

	NG Extraction			NG Processing			NG Transport		
	85 %	100 %	115 %	85 %	100 %	115 %	85 %	100 %	115 %
CSU-N Total Efficiency	31.28 % (0.71 %)	31.06 %	30.90 % (−0.52 %)	31.09 % (0.10 %)	31.06 %	31.03 % (−0.10 %)	32.01 % (3.06 %)	31.06 %	30.14 % (−2.96 %)
CSU-N Efficiency Drop	45.12 % (−0.84 %)	45.50 %	45.79 % (0.64 %)	45.46 % (−0.09 %)	45.50 %	45.57 % (0.15 %)	43.85 % (−3.63 %)	45.50 %	47.13 % (3.58 %)

Table 6
Sensitivity analysis of coal preparation stages in CSU-C.

	Coal Extraction			Coal Processing			Coal Transport		
	85 %	100 %	115 %	85 %	100 %	115 %	85 %	100 %	115 %
CSU-C Total Efficiency	21.88 % (0.05 %)	21.87 %	21.85 % (−0.09 %)	21.87 % (0.00 %)	21.87 %	21.86 % (−0.05 %)	21.88 % (0.05 %)	21.87 %	21.86 % (−0.05 %)
CSU-C Efficiency Drop	61.49 % (−0.03 %)	61.51 %	61.55 % (0.07 %)	61.51 % (0.00 %)	61.51 %	61.53 % (0.03 %)	61.50 % (−0.02 %)	61.51 %	61.53 % (0.03 %)

Table 7
Sensitivity analysis of CCS stages in CSU-N and CSU-C.

	CO2 Capture			CO2 Compression		
	85 %	100 %	115 %	85 %	100 %	115 %
CSU-N Total Efficiency	31.76 % (2.25 %)	31.06 %	30.46 % (−1.93 %)	31.15 % (0.29 %)	31.06 %	30.97 % (−0.29 %)
CSU-N Efficiency Drop	44.28 % (−2.68 %)	45.50 %	46.55 % (2.31 %)	45.34 % (−0.35 %)	45.50 %	45.67 % (0.37 %)
CSU-C Total Efficiency	22.85 % (4.48 %)	21.87 %	20.97 % (−4.12 %)	22.04 % (0.78 %)	21.87 %	21.70 % (−0.78 %)
CSU-C Efficiency Drop	59.83 % (−2.73 %)	61.51 %	63.10 % (2.58 %)	61.22 % (−0.47 %)	61.51 %	61.83 % (0.52 %)
	CO2 Transport			CO2 Storage		
	85 %	100 %	115 %	85 %	100 %	115 %
CSU-N Total Efficiency	31.09 % (0.10 %)	31.06 %	31.04 % (−0.06 %)	31.09 % (0.10 %)	31.06 %	31.04 % (−0.06 %)
CSU-N Efficiency Drop	45.46 % (−0.09 %)	45.50 %	45.55 % (0.11 %)	45.45 % (−0.11 %)	45.50 %	45.55 % (0.11 %)
CSU-C Total Efficiency	22.02 % (0.69 %)	21.87 %	21.70 % (−0.78 %)	21.90 % (0.14 %)	21.87 %	21.83 % (−0.18 %)
CSU-C Efficiency Drop	61.21 % (−0.49 %)	61.51 %	61.82 % (0.50 %)	61.44 % (−0.11 %)	61.51 %	61.59 % (0.13 %)

Table 8
Sensitivity analysis of natural gas preparation stages in CSA-N.

	NG Extraction			NG Processing			NG Transport		
	85 %	100 %	115 %	85 %	100 %	115 %	85 %	100 %	115 %
CSA-N Total Efficiency	29.56 % (0.85 %)	29.31 %	29.18 % (−0.44 %)	29.33 % (0.07 %)	29.31 %	29.29 % (−0.07 %)	30.44 % (3.86 %)	29.31 %	28.31 % (−3.41 %)
CSA-N Efficiency Drop	48.14 % (−0.89 %)	48.57 %	48.80 % (0.47 %)	48.54 % (−0.06 %)	48.57 %	48.61 % (0.08 %)	46.60 % (−4.06 %)	48.57 %	50.34 % (3.64 %)

5. Conclusion

The integration of CCS in fossil fuel power plants introduces significant energy penalties, affecting total efficiency and increasing energy consumption across multiple stages. Fuel preparation, i.e., fuel extraction, processing, and transportation, emerges as a dominant factor in natural gas plants, contributing 81.2–85.7 % of the total energy requirement, compared to 7.4–10.4 % in coal plants. Efficiency losses are substantial at higher CO_2 capture rates, with natural gas and coal plants experiencing up to 49% and 63% reductions, respectively, at 100% capture. At 85 % capture, efficiency penalties are lower: 24.95–25.20 % for natural gas and 59.44–60.08 % for coal.

The sensitivity analysis highlights that CO_2 capture is the most energy-intensive stage, with significant efficiency impacts. Natural gas transportation distance also shows high variability, reinforcing the importance of optimizing transport logistics. When transportation distance doubles, total efficiency drops 15.13 % in CSU-N and 16.62 % in CSA-N, demonstrating the critical role of fuel transport in overall efficiency.

Despite the substantial efficiency losses, CCS remains essential for reducing CO_2 emissions. At 95 % capture, natural gas power plants avoid 3.6 Mt CO_2/year, while coal power plants prevent 8.43 Mt CO_2/year. Implementing heat recovery systems and utilizing hybrid solvents can reduce the energy demands of CO_2 capture, helping to mitigate associated efficiency losses. Additionally, policy support through carbon pricing and targeted subsidies, will be essential to facilitate widespread CCS adoption, particularly in coal-dependent regions like Australia. Overall, optimizing CO_2 capture rates, improved transportation methods, and efficient fuel management strategies are key to balancing emission reductions with energy demands of CCS employment.

CRediT authorship contribution statement

Enrique García-Tenorio Corcuera: Writing – review & editing, Writing – original draft, Methodology, Investigation. **Fontina Petrakopoulou:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial

Table 9
Sensitivity analysis of coal preparation stages in CSA-C.

	Coal Extraction			Coal Processing			Coal Transport		
	85 %	100 %	115 %	85 %	100 %	115 %	85 %	100 %	115 %
CSA-C Total Efficiency	21.46 % (0.14 %)	21.43 %	21.41 % (−0.09 %)	21.44 % (0.05 %)	21.43 %	21.43 % (0.00 %)	21.45 % (0.09 %)	21.43 %	21.42 % (−0.05 %)
CSA-C Efficiency Drop	62.26 % (−0.05 %)	62.29 %	62.32 % (0.05 %)	62.28 % (−0.02 %)	62.29 %	62.30 % (0.02 %)	62.26 % (−0.05 %)	62.29 %	62.32 % (0.05 %)

Table 10
Sensitivity analysis of CCS stages in CSA-N and CSA-C.

	CO2 Capture			CO2 Compression		
	85 %	100 %	115 %	85 %	100 %	115 %
CSA-N Efficiency	29.95 % (2.18 %)	29.31 %	28.78 % (−1.81 %)	29.39 % (0.27 %)	29.31 %	29.23 % (−0.27 %)
CSA-N Drop	47.46 % (−2.29 %)	48.57 %	49.52 % (1.96 %)	48.44 % (−0.27 %)	48.57 %	48.72 % (0.31 %)
CSA-C Efficiency	22.36 % (4.34 %)	21.43 %	20.58 % (−3.97 %)	21.60 % (0.79 %)	21.43 %	21.27 % (−0.75 %)
CSA-C Drop	60.70 % (−2.55 %)	62.29 %	63.79 % (2.41 %)	61.98 % (−0.50 %)	62.29 %	62.60 % (0.50 %)
	CO2 Transport			CO2 Storage		
	85 %	100 %	115 %	85 %	100 %	115 %
CSA-N Efficiency	29.34 % (0.10 %)	29.31 %	29.29 % (−0.07 %)	29.34 % (0.10 %)	29.31 %	29.29 % (−0.07 %)
CSA-N Drop	48.52 % (−0.10 %)	48.57 %	48.62 % (0.10 %)	48.53 % (−0.08 %)	48.57 %	48.61 % (0.08 %)
CSA-C Efficiency	21.64 % (0.98 %)	21.43 %	21.24 % (−0.89 %)	21.49 % (0.28 %)	21.43 %	21.39 % (−0.19 %)
CSA-C Drop	61.92 % (−0.59 %)	62.29 %	62.64 % (0.56 %)	62.22 % (−0.11 %)	62.29 %	62.36 % (0.11 %)

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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